Tritium beta polarization

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2.1. The Mott scattering method

Various methods are available for measuring the polarization of electron or positron beams. The measurements may be direct, taking advantage of polarization dependent cross sections, e.g. Møller and Bhabha scattering on polarized electrons, Mott scattering on heavy nuclei and, especially for positrons, annihilation with polarized electrons or positronium formation. The measurements may also be indirect, transferring the longitudinal polarization of the β-particles to circular polarization of γ-radiation e.g. by bremsstrahlung; this circular polarization is then detected. For a detailed account of these methods we refer to reviews of, for example, Tolhoek (Tol56), Kofoed-Hansen and Christensen (Kof62), Frauenfelder (Fra68), Wu and Moszkowski (Wu66) and Schopper (Sch66).

We briefly describe the Mott scattering method, which was used for the experiment described in this thesis. It is the best method available for electron polarization measurements in the energy region below about 500 keV. The method is based on the spin dependence of the scattering of electrons by the Coulomb field of a nucleus. The physical mechanism that underlies this spin dependence is the spin-orbit interaction between the magnetic moment connected with the spin of the electron and the magnetic field caused by the motion of the nuclear charge (as seen in the rest frame of the electron). The attractive potential between electron and nucleus due to the Coulomb interaction, is influenced by the relative orientation of this magnetic field and the magnetic moment of the electron.

Mott (Mot29,32) was the first to give a relativistic quantum-mechanical treatment of single scattering of electrons by atomic nuclei. He showed that initially unpolarized electrons become transversely polarized after the scattering. The spin orientation is perpendicular to the plane of scattering. The degree of transverse polarization, usually denoted as S, depends on the scattering angle θ, the energy E of the electrons and the atomic number Z

of the nuclei. The function S is commonly called the Mott (asymmetry) function or the Sherman function (see later).

If, on the other hand, the electrons are initially transversely polarized with degree of polarization P_T, the differential scattering cross section is asymmetric:

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma_o}{d\Omega}(\theta)\left[1 - P_T S(\theta)\sin\phi\right], \qquad (2.1)$$

where $d\sigma_O/d\Omega$ is the polarization independent differential cross section, θ is the polar angle of scattering and ϕ is the azimuthal angle of scattering relative to the plane of the initial momentum $\vec{p}$ and polarization vector $\vec{P}$ of the electrons. Eq. 2.1 gives

$$\frac{I(\theta,\phi+\pi) - I(\theta,\phi)}{I(\theta,\phi+\pi) + I(\theta,\phi)} = P_T S(\theta)\sin\phi, \qquad (2.2)$$

where I denotes the observed intensity at the indicated angles. Thus, a measurement of the scattering asymmetry yields a value for P_T. The largest asymmetry is observed in the plane perpendicular to the initial momentum and polarization vector of the electrons ($\phi = 90^o$ or 270^o). The asymmetry in this plane is usually denoted as the "left-right asymmetry":

$$\delta \equiv \frac{L - R}{L + R} = P_T S(\theta), \qquad (2.3)$$

where "left" is defined as the direction of the vector $\vec{P} \times \vec{p}$.

The scattering cross section and the Mott function can be written as

$$\frac{d\sigma_o}{d\Omega} = |f|^2 + |g|^2 \text{ and } S = i(fg^* - gf^*)/(|f|^2 + |g|^2). \qquad (2.4)$$

The complex scattering amplitudes f and g depend on θ, E and Z. These amplitudes, with the aid of which Coulomb scattering of polarized electrons can be completely described, are obtained by solving the Schrödinger equation for the scattering process and are usually expressed in terms of partial wave expansions (Ros61).

The function S has been calculated, on the basis of eq. 2.4, for various values of θ, E and Z by Sherman (She56) for scattering by a point nucleus and, more recently, including screening by atomic electrons, by Lin (Lin64), by Holzwarth and Meister (Hol64) and by Bühring (Büh68). Values for S have been obtained from double-scattering experiments by, amongst others, Mikaēlyan et al. (Mik63), Nelson and Pidd (Nel59) and van Klinken (Kli66a). In such experiments an initially unpolarized beam is scattered twice, choosing similar conditions for the first and second scattering. Then, in the limit of zero scatterer thicknesses, the observed asymmetry becomes essentially S^2. Figs. 2.1a and b illustrate the dependence of S from θ and E for electron scattering on gold nuclei. Calculated and measured values agree reasonably well at electron energies above about 100 keV; at lower energies, however, large discrepancies exist (see also ref. Boe71).

For measuring β-polarization by Mott scattering one has to transform the longitudinal polarization to a transverse one. This can be achieved with electrostatic deflection over about 90° (as was used for this work), with Coulomb scattering by low-Z scatterers or with crossed electric and magnetic fields ("Wien filter"). Details may be found in the mentioned reviews.

In an actual experiment the theoretical quantity S in eq. 2.3 has to be replaced by an effective S-value, to be denoted as S_{an}, which includes effects of plural and multiple scattering in foils of finite thickness, of finite solid angles and of backscattering by walls. This polarimeter efficiency S_{an} may be obtained from a double-scattering experiment, as was done for this work, or it may be derived from calculated S-values (see a discussion in the subsequent section).

Optimum conditions for electron polarization analysis by means of Mott scattering are: a high-Z foil, for example of gold, as scatterer; backward-angle scattering over about 105°-125°, and electron energies in the range 50 - 500 keV. The foil should be thin, because S_{an} decreases with increasing foil thickness due to plural and multiple scattering. Since scattered intensities increase approximately linearly with increasing foil thickness, an optimum foil thickness can be found (see ref. Kli66a for details).

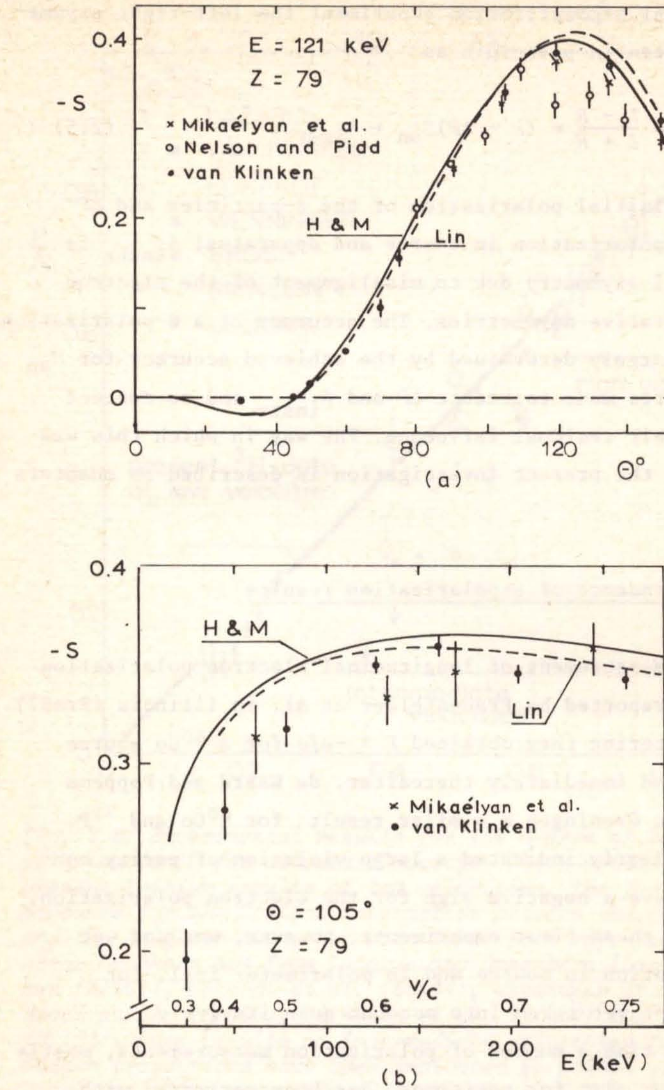

Fig. 2.1. Experimental and calculated results for the Mott function for electron scattering on gold nuclei. Both figures were taken from ref. Kli66a. References are given in the main text; H & M denotes Holzwarth and Meister.

In an actual β-polarization experiment the left-right asymmetry can be written in principle as

$$\delta = \frac{L - R}{L + R} = (P - \Delta P)S_{an} + \delta_{instr}. \qquad (2.5)$$

Here, P is the initial polarization of the β-particles and ΔP accounts for depolarization in source and apparatus; δ_{instr} is the instrumental asymmetry due to misalignment of the electron beam or to apparative asymmetries. The accuracy of a β-polarization experiment is largely determined by the achieved accuracy for S_{an} and by the efforts made to reduce ΔP and δ_{instr} and to correct properly for their residual influence. The way in which this was accomplished in the present investigation is described in chapters 5, 6 and 7.

2.2. Energy dependence of β-polarization results

The first measurement of longitudinal electron polarization in β-decay was reported by Frauenfelder et al. in Illinois (Fra57). Using Mott scattering they obtained $P \simeq -v/c$ for a ^{60}Co source. Independently and immediately thereafter, de Waard and Poppema (Waa57) found in Groningen a similar result for ^{60}Co and ^{32}P. These results clearly indicated a large violation of parity conservation and gave a negative sign for the electron polarization. The accuracy of these first experiments, however, was not yet high; depolarization in source and in polarimeter foil, for example, were not yet taken into account quantitatively.

Since that time a number of polarization measurements, mostly for electrons but also for positrons, has been performed with various methods and with increasing accuracy. The measurements on allowed decays were performed mainly in order to study β-decay theory, while results on forbidden transitions could sometimes be used for obtaining information on nuclear matrix elements. A fairly complete compilation of results from the late fifties and early sixties has been given by Kofoed-Hansen and Christensen (Kof62). Schopper (Sch66) compiled data on allowed decays obtained before 1965.

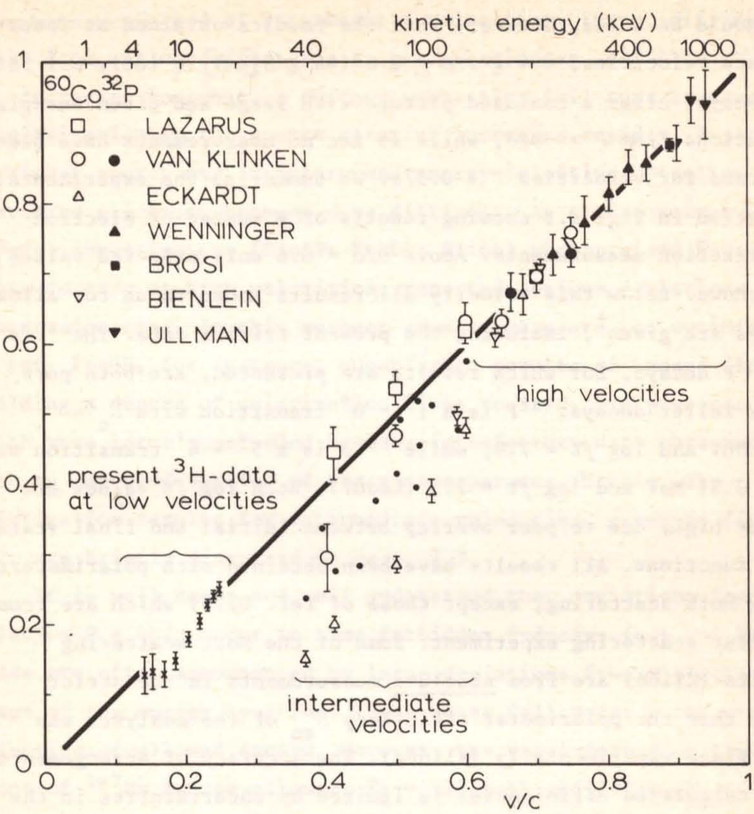

Fig. 2.2. Experimental results for the degree of longitudinal polarization P for allowed β^--decays. The compilation includes the present tritium results at low velocities. The factor Λ, which accounts for the Coulomb interaction between the emitted electron and the daughter atom, has been taken from ref. Beh69. Data with error brackets are from Lazarus and Greenberg (Laz70), van Klinken (Kli66), Eckardt et al. (Eck64), Wenninger et al. (Wen67), Brosi et al. (Bro62), Bienlein et al. (Bie59) and Ullman et al. (Ull61). Some results at intermediate velocities for first-forbidden transitions have been indicated by points without error brackets: ^{147}Pm data from refs. Kli66 and Eck64; ^{198}Au data from refs. Kli66 and Ava62. Eckardt et al. (Eck64) did not correct their results for depolarization in the source (see remark in sect. 7.3). The straight line represents the relation $P = -\Lambda v/c$.

It turns out that, after some initial discrepancies, all data on allowed decays obtained for electron or positron velocities larger than $0.6c$ ($E > 128$ keV) agree with $P = -v/c$ for electrons and $P = +v/c$ for positrons. Thus, a firm belief in the validity of these relations for the whole velocity range has grown.

It should be noted, however, that the results obtained at intermediate velocities, $0.4 \lesssim v/c \lesssim 0.6$ ($46 \lesssim E[\mathrm{keV}] \lesssim 128$), all for β^--decays, offer a confused picture with large and often unexplained deviations from $P = -v/c$, while so far no measurements have been reported for velocities $v < 0.37c$. We summarize the experimental situation in fig. 2.2 showing results of a number of electron polarization measurements. Above $v/c = 0.6$ only selected values are shown. Below this velocity all results known to us for allowed decays are given†, including the present tritium data. The ^{60}Co and ^{32}P decays, for which results are presented, are both pure Gamow-Teller decays: ^{32}P is a $1^+ \rightarrow 0^+$ transition with E_o = 1.71 MeV and log ft = 7.9, while ^{60}Co is a $5^+ \rightarrow 4^+$ transition with E_o = 0.31 MeV and log ft = 7.5 (Led67). Both log ft values are rather high, due to poor overlap between initial and final state wave functions. All results have been obtained with polarimeters using Mott scattering, except those of ref. Ull61 which are from a Møller scattering experiment. Some of the Mott scattering results (Kli66) are from absolute measurements in the strict sense that the polarimeter efficiency S_{an} of the analyser was determined experimentally (Kli66a). The accuracy of arrangements with calculated efficiencies is limited by uncertainties in the adopted S_{an}-values, perhaps more seriously than realized by some of the investigators. For the best theoretical Mott functions S for single scattering by gold nuclei (Lin64; Büh68) a computational error of 1% has been estimated. However, this computed value must be converted to the efficiency S_{an} of the actual polarimeter (see previous section). In our experience this procedure excludes accuracies better than 2 or 3% for polarization results based on calculated S_{an}-values. Within this accuracy the v/c-relation is followed very well for velocities above $0.6c$. It is at lower energies that the situation becomes confusing.

Relatively few experiments, all using Mott scattering,

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†Recently, we were informed about an investigation of Ryu (Ryu75) on the polarization of β^--particles emitted in the allowed decay of ^{45}Ca (E_o = 255 keV). Ryu reports that his results indicate a polarization less than 30% of v/c at an energy of 79 keV (v/c = 0.5). This very low value has not been included in the compilation of fig. 2.2.

have been performed at intermediate velocities. There, difficulties arise from various effects: e.g. the polarimeter efficiency S_{an} decreases somewhat, a thinner scattering foil must be used, depolarization in the source material increases rapidly, β-particles of higher energy may interfere and energy-selective detection of scattered electrons becomes more difficult. As a consequence several investigators (Bie59; Eck64; Kli66) who obtained P-values close to $-v/c$ at high velocities, reported serious deviations at lower velocities. In this respect some surveys are too optimistic. In ref. Fra68, for instance, unpublished results of Ladage (Lad61) yielding a degree of polarization close to $-v/c$, are presented†, which were later superseded by less satisfactory data obtained with an improved version of the same apparatus (Eck64). The polarization results for intermediate velocities given in fig. 2.2, are briefly discussed in sect. 7.3.

It is well known and well understood that deviations from the relation $P = -v/c$ occur in some forbidden β-decays (e.g. of RaE). These are often accompanied by large deviations from a statistical shape of the energy spectrum. These cases fall outside the present selection of allowed decays. However, the first-forbidden transitions of ^{147}Pm (shape-allowed; E_o = 225 keV) and ^{198}Au (E_o = 962 keV), that are expected to follow the v/c-relation, have been included in the compilation of fig. 2.2 (for clarity by points without error brackets).

For the decay of high-Z nuclei an appreciable deviation is expected at lower energies because of the Coulomb interaction between the emitted electron and the daughter atom. This effect is usually incorporated in a factor Λ by writing $P = -\Lambda v/c$. For electrons Λ is smaller than unity; the deviation from unity increases with decreasing energy. If necessary, we corrected the data of fig. 2.2, using tables of Behrens and Jänecke (Beh69). Finite nuclear size effects are accounted for in these tables under the assumption of a uniform charge distribution inside the nucleus. The deviation of Λ from unity is negligible for the

†Unfortunately, the result at the lowest energy in ref. Fra68 (p. 1451), that belongs to the superseded data of Ladage, has been attributed by a misprint to Ullman et al.

tritium (< 0.1%) and the ^{32}P ($\lesssim$ 0.2%) data. It amounts to 3.3% for ^{60}Co at v/c = 0.37, to 6% for ^{198}Au at v/c = 0.45 and to 9% for ^{147}Pm at v/c = 0.37.

The influence of second-forbidden matrix elements on the polarization is of order $(kR)^2 \approx 10^{-4}p'^2$ or $(v_N/c)(kR) \approx 10^{-3}p'$, depending on the type of matrix element concerned (Mor59). Here, v_N is the average velocity of the nucleons in the nucleus ($v_N/c \approx$ 0.1), R is the nuclear radius, k is the wave number of the emitted electron and p' is its momentum in units m_ec. The influence is negligible small for the data of fig. 2.2: $\lesssim 3\cdot10^{-4}$ for tritium, $\lesssim 2\cdot10^{-3}$ for ^{60}Co and $\lesssim 3\cdot10^{-3}$ for ^{32}P.

We concur with several investigators (Bie59; Eck64; Laz70) in feeling the need for reliable low-velocity data, because any real deviation from $P = -v/c$ would be in serious contradiction with the present theory of β-interaction. The aim of the present investigation is to obtain accurate polarization results at the lowest possible energies in order to check whether or not there are real deviations from the theory at low velocities.

In this context we remark that a factor v/c also occurs in equations describing related phenomena like β-asymmetry of polarized nuclei and β-γ circular polarization correlation (Sch66). The first parity experiments were the measurements of the β-asymmetry of polarized nuclei by Wu et al. (Wu57) on ^{60}Co and ^{58}Co, followed by measurements of Postma et al. (Pos57,58,60) on ^{58}Co and ^{52}Mn. These experiments cover β-velocities 0.4 < v/c < 0.8. Steffen (Ste59) and later Lobashov and Nazarenko (Lob62) investigated the v/c-dependence of the β-γ circular polarization correlation for ^{60}Co at electron velocities between 0.52c and 0.77c. These four groups found a rather satisfactory v/c-dependence of the observed effects, though with deviations of about 20% at velocities below ≈ 0.6c, where large corrections were needed (e.g. for the influence of scattering in source and apparatus).